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## Time-Accurate Simulations of Incompressible Flows with Moving Boundaries

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NASA Ames Research Center

Workshop on Numerical Simulations of  
Incompressible Flows  
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## Outline



- INTRODUCTION
  - Status
  - Major Drivers of the Current Work
- OBJECTIVE
- SOLUTION METHODS
  - Formulation / Approach
  - Summary of Solver Development
  - Current Challenges
- HEC APPLICATIONS
  - Parallel Implementation
  - Application to SSME Turbopump
- DISCUSSION

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## Status from Applications Point of View



- Applications to Real-World Problems
  - N-S solution of full configuration was a big goal in the 80s
  - Numerical procedures and computing hardware have been advanced enabling simulation of complex configurations
- Some Examples of Successful Applications
  - Components of liquid rocket engine
  - Hydrodynamics (Submarines, propellers, ...)
  - Ground vehicles (automobile aerodynamics, internal flows...)
  - Biofluid problems (artificial heart, lung, ...)
  - Some Earth Science problems
- Current Challenges
  - For integrated systems analysis, computing requirement is very large
    - ⇒ Analysis part is still limited to low fidelity approach
  - For high-fidelity analysis, especially involving unsteady flow, long turn-around time is often a bottle neck ⇒ Acceleration of solution time is required

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## Major Drivers of Current Work



- To provide computational tools as an economical option for developing future space transportation systems (i.e. RLV subsystems development)
  - Impact on component design ⇒ Rapid turn-around of high-fidelity analysis
  - Increase durability/safety ⇒ Accurate quantification of flow (i.e. prediction of low-induced vibration)
  - Impact on system performance ⇒ More complete systems analysis using high-fidelity tools
- Target
  - Turbo-pump component analysis ⇒ Entire sub-systems simulation
  - Computing requirement is large:
    - ⇒ The goal is to achieve 1000 times speed up over what was possible in 1992

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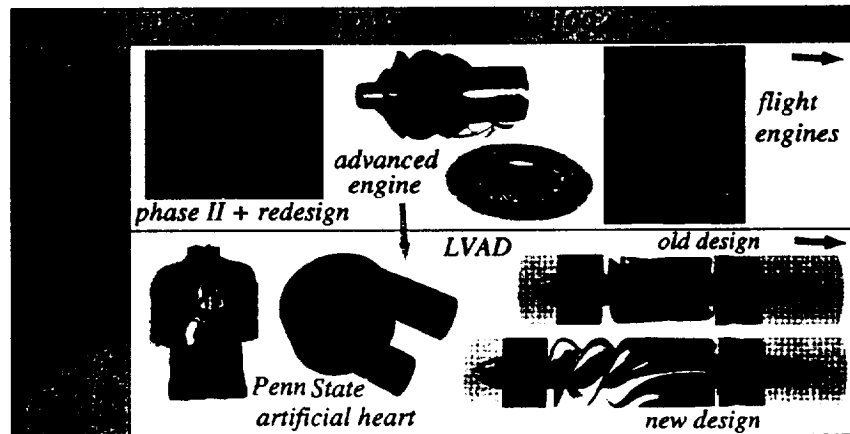


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## Objectives



- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump.



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## INS3D - Incompressible N-S Solver



### \*\* Parallel version : Based on INS3D-UP

- MPI and MLP parallel versions
- Structured, overset grid orientation
- Moving grid capability
- Based on method of artificial compressibility
- Both steady-state and time-accurate formulations
- 3<sup>rd</sup> and 5<sup>th</sup>-order flux difference splitting for convective terms
- Central differencing for viscous terms
- One- and two-equations turbulence models
- Several linear solvers : GMRES, line-relaxation, LU-SGS, point relaxation, ILU(0),...

### • HISTORY

- \*\* 1982-1987 Original version of INS3D - Kwak, Chang
- \*\* 1988-1999 Three different versions were devoped :
  - INS3D-UP / Rogers, Kiris, Kwak
  - INS3D-LU / Yoon, Kwak
  - INS3D-FS / Rosenfeld, Kiris, Kwak



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## Time Accurate Formulation



- Time-integration scheme

### Artificial Compressibility Formulation

- Introduce a pseudo-time level and artificial compressibility
- Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

### Pressure Projection Method

- Solve auxiliary velocity field first, then enforce incompressibility condition by solving a Poisson equation for pressure.

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## Artificial Compressibility Method



### Time-Accurate Formulation

- Discretize the time term in momentum equations using second-order three-point backward-difference formula

$$\left( \frac{\partial U}{\partial \xi} + \frac{\partial V}{\partial \eta} + \frac{\partial W}{\partial \zeta} \right)^{n+1} = 0 \quad \frac{3q^{n+1} - 4q^n + q^{n-1}}{2\Delta t} = -r^{n+1}$$

- Introduce a pseudo-time level and artificial compressibility.
- Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

$$\frac{1}{\Delta \tau} (p^{n+1,m+1} - p^{n+1,m}) = -\beta \nabla q^{n+1,m+1}$$

$$\frac{1.5}{\Delta t} (q^{n+1,m+1} - q^{n+1,m}) = -r^{n+1,m+1} - \frac{3q^{n+1,m} - 4q^n + q^{n-1}}{2\Delta t}$$

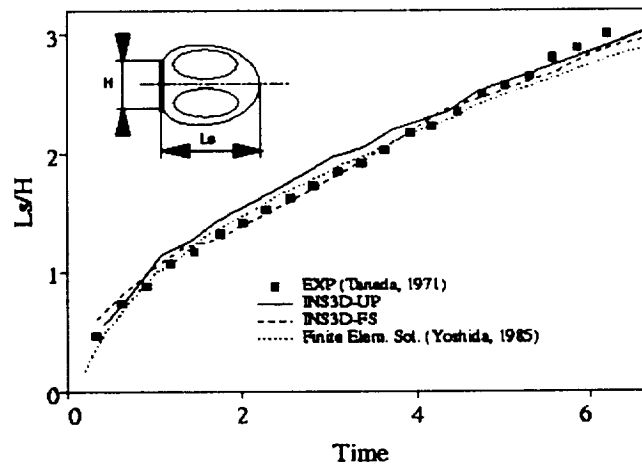
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## Impulsively Started Flat Plate at 90°



### • Time History of Stagnation Point



## Current Challenges



- Challenges where improvements are needed
  - Time-integration scheme, convergence
  - Moving grid system, zonal connectivity
  - Parallel coding and scalability
- As the computing resources changed to parallel and distributed platforms, computer science aspects become important such as
  - Scalability (algorithmic & implementation)
  - Portability, transparent coding etc.
- Computing resources
  - "Grid" computing will provide new computing resources for problem solving environment
  - High-fidelity flow analysis is likely to be performed using "super node" which is largely based on parallel architecture



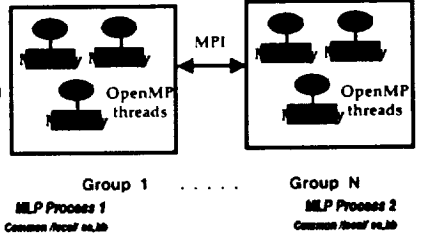
## INS3D Parallelization



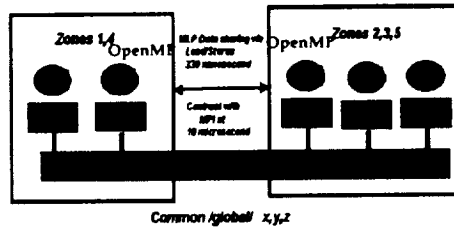
- INS3D-MPI  
(coarse grain)  
T. Faulkner & J. Dacles



- INS3D-MPI / Open MP  
MPI (coarse grain) + OpenMP (fine grain)  
Implemented using CAPO/CAPT tools  
H. Jin & C. Kiris



- INS3D-MLP  
C. Kiris



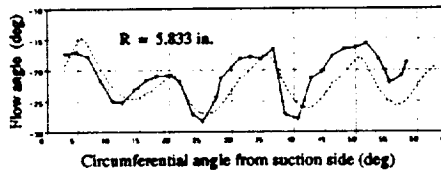
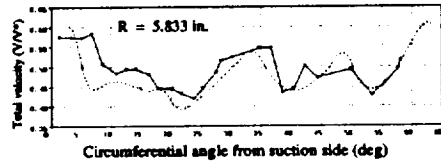
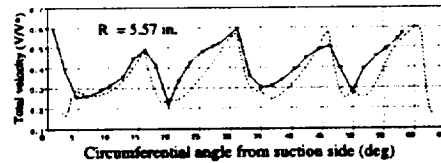
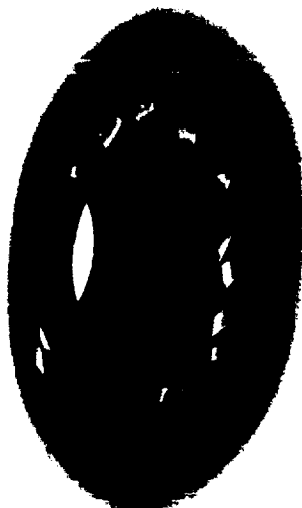
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## Previous Work (SSME Impeller)



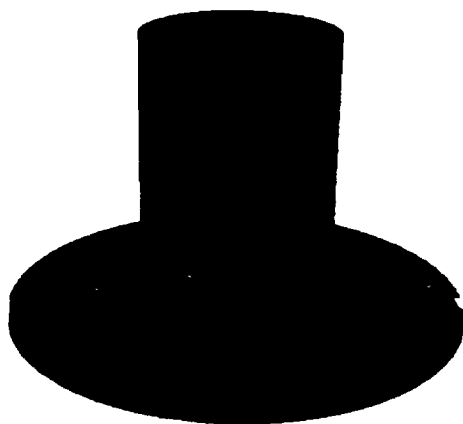
Pressure



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## Space Shuttle Main Engine Turbopump



### Inlet Guide Vane (IGV)

- 15 Blades
- Pitch,  $p = 24$  degrees
- Blade Inlet Angle (mean),  $\beta_{IGV,i} = 90$  degrees
- Blade Exit Angle (mean),  $\beta_{IGV,e} = 45$  degrees

Clearance between IGV and Impeller,  $x = 0.12$  inches

### Impeller

- 6+6+12 Unshrouded Design
- Pitch,  $p = 60$  degrees
- Blade Inlet Angle (mean),  $\beta_{imp,i} = 23$  degrees
- Blade Exit Angle (mean),  $\beta_{imp,e} = 65$  degrees
- Clearance between blade LE and Shroud,  $r = 0.0056$  inches
- Clearance between blade TE and Shroud,  $r = 0.0912$  inches

Clearance between Impeller and Diffuser,  $r = 0.050$  inches

### Diffuser

- 23 Blades
- Pitch,  $p = 15.652$  degrees
- Blade Inlet Angle (mean),  $\beta_{diff,i} = 12$  degrees
- Blade Exit Angle (mean),  $\beta_{diff,e} = 43$  degrees

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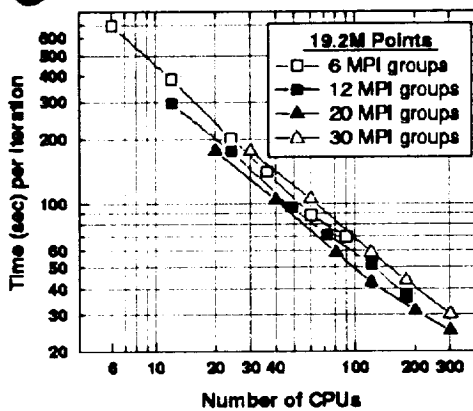
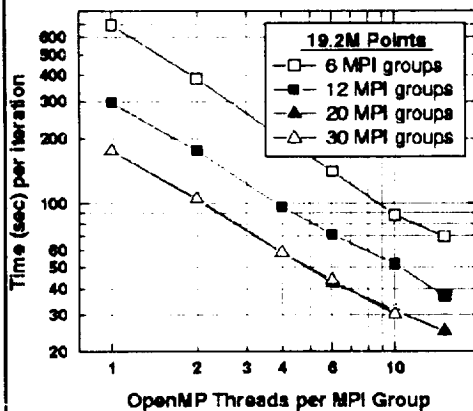


## INS3D Parallelization



MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller  
60 zones / 19.2 Million points



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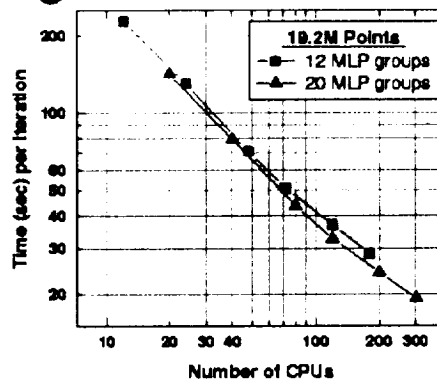
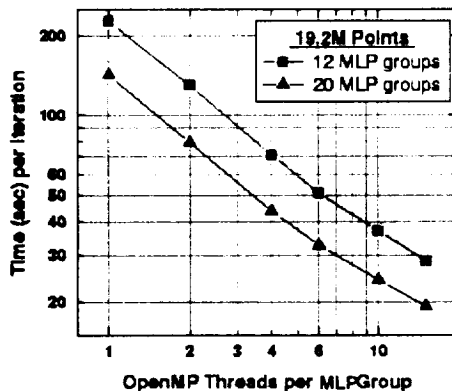


## INS3D Parallelization



INS3D-MLP (NAS MLP no pin-to-node)  
/ OpenMP

TEST CASE : SSME Impeller  
60 zones / 19.2 Million points



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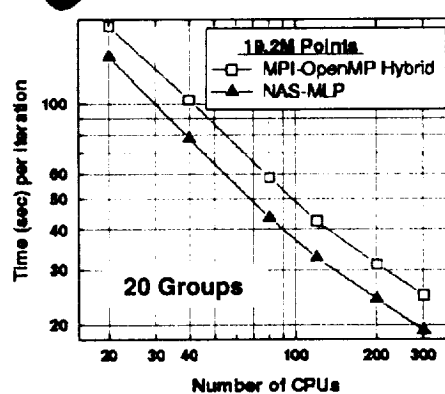
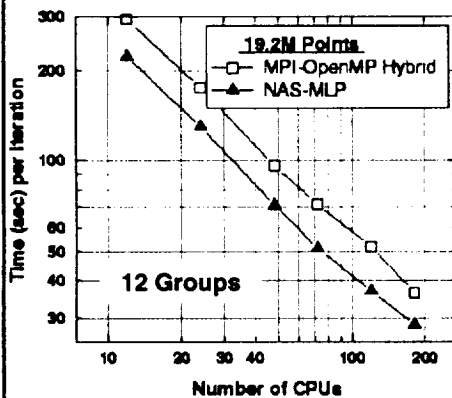


## INS3D Parallelization



INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller  
60 zones / 19.2 Million points



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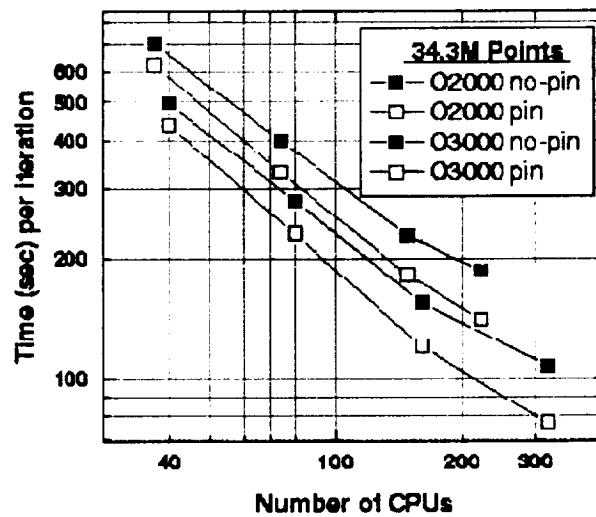


## Parallel Implementation of INS3D



INS3D-MLP / 40 Groups

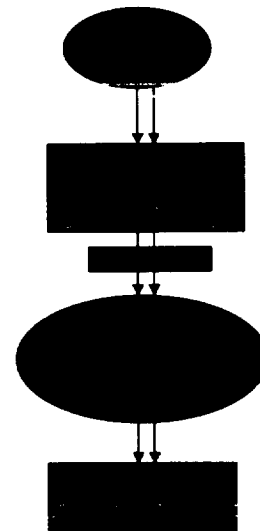
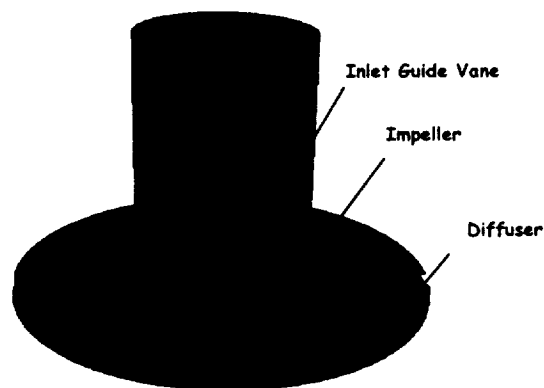
RLV 2<sup>nd</sup> Gen Turbo pump  
114 Zones / 34.3 M grid points



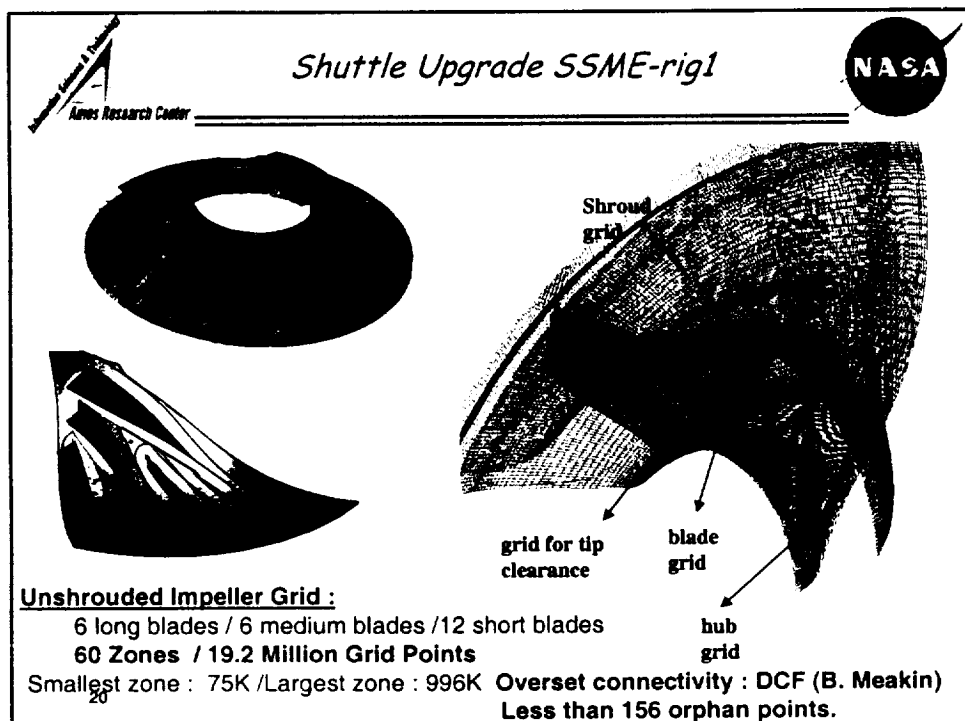
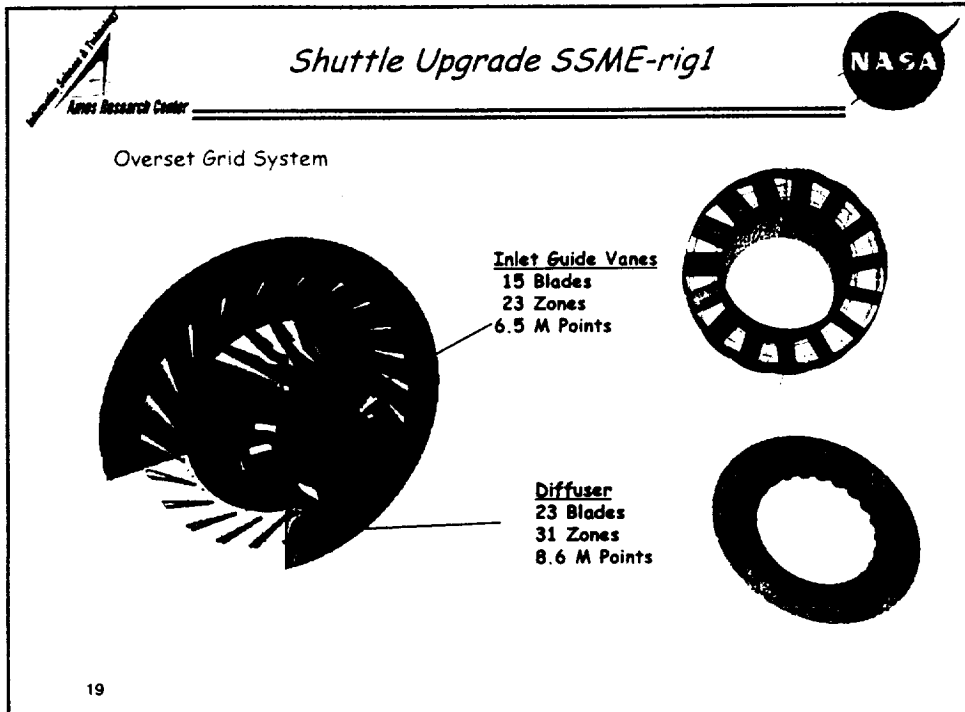
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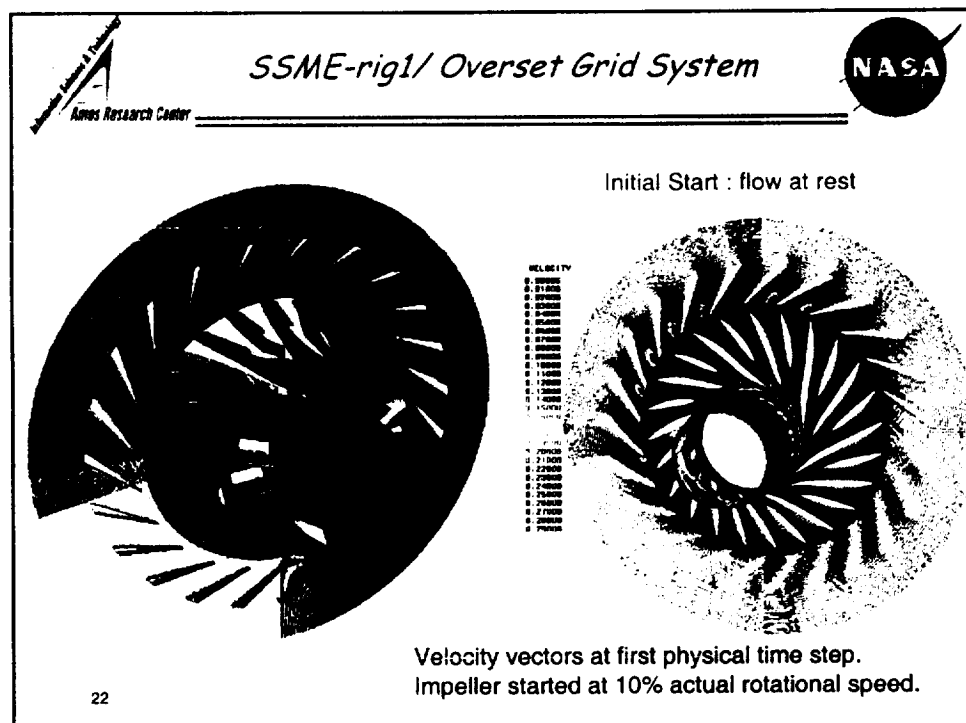
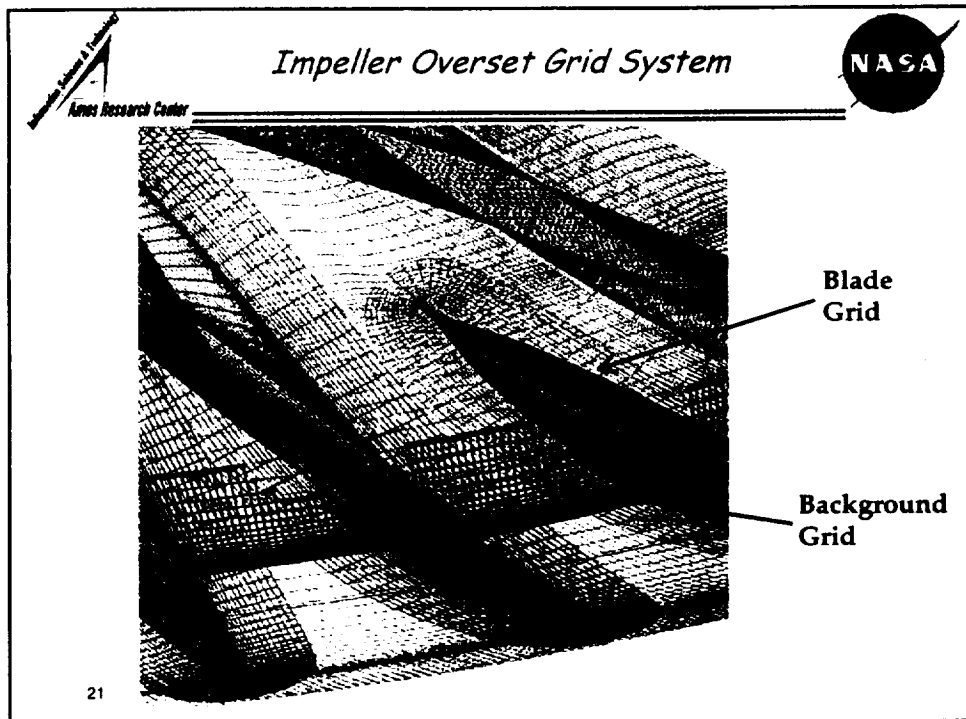


## RLV 2<sup>nd</sup> Gen Turbopump (SSME Rig1)



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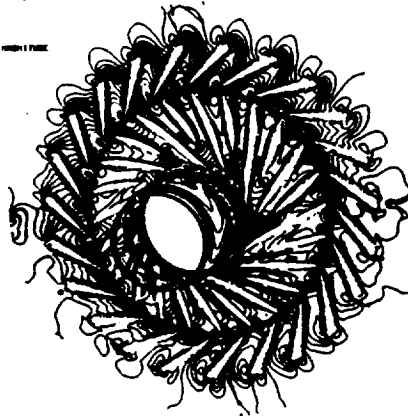




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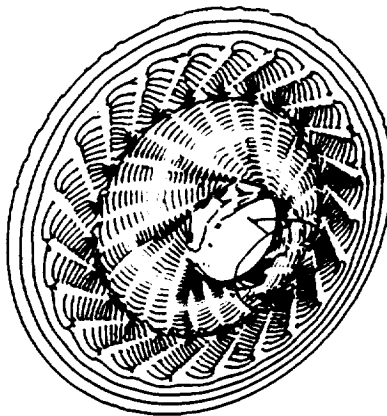


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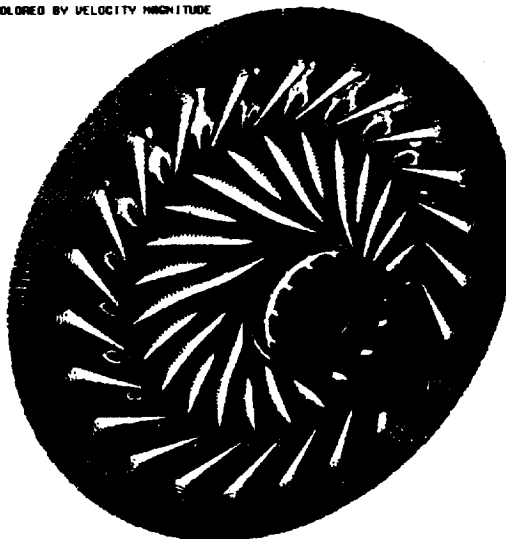
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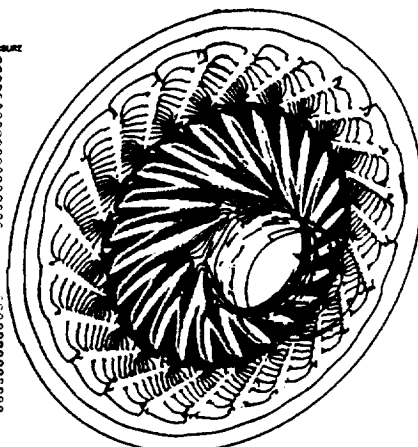
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VELOCITY COLORED BY VELOCITY MAGNITUDE

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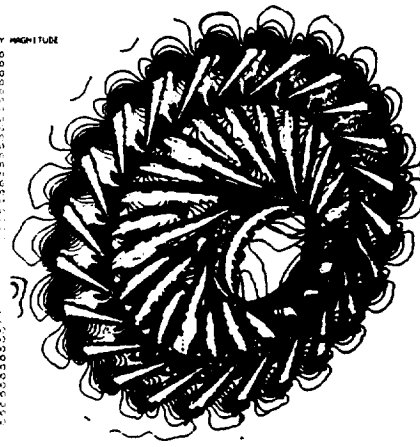


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3	640000
2	660000
3	680000
2	700000
3	720000
2	740000
3	760000
2	780000
3	800000
2	820000
3	840000
2	860000
3	880000
2	900000
3	920000
2	940000
3	960000
2	980000
3	1000000



### VELOCITY MAGNITUDE

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## SSME-rig1 / Initial start



TIME STEP 18 / Impeller rotated 8-degrees at 100% of design speed

PRESSURE

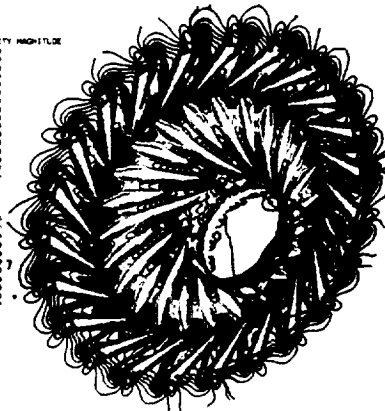
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2	00000
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0	00000
-1	80000
-1	60000
-1	40000
-1	20000
-1	00000
-2	80000
-2	60000
-2	40000
-2	20000
-2	00000



PRESSURE

VELOCITY MAGNITUDE

2	80000
2	60000
2	40000
2	20000
2	00000
1	80000
1	60000
1	40000
1	20000
1	00000
0	80000
0	60000
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0	00000
-1	80000
-1	60000
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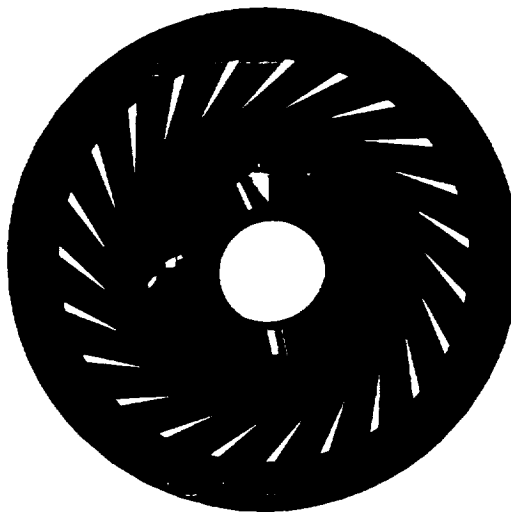


VELOCITY MAGNITUDE

27



## Shuttle Upgrade SSME-rig1



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- 34.3 Million Points

- 800 physical time steps in one rotation.

\*One physical time-step requires less than 20 minutes wall time with 80 CPU's on Origin 2000.

One complete rotation requires one-week wall time with 80 CPUs.

\*Currently I/O is through one processor. Timing will be improved with parallel I/O since time-accurate computations are I/O intensive. With further improvements several impeller rotations can be completed in one week.



## Summary



- Unsteady SSME-rig1 start-up procedure from the pump at rest has been initiated by using 34.3 Million grid points.
- Computational model for the SSME-rig1 is completed. Moving boundary capability is obtained by using DCF module in OVERFLOW-D.
- MPI /Open MP hybrid parallel code has been benchmarked.
- MLP shared memory parallelism has been implemented in INS3D, and benchmarked.
- MLP/OpenMP version requires 19-25% less computer time than MPI/OpenMP version. Pin-to-node for MLP version is implemented. 40% less computer time is required in the new version.
- Time-accurate features of methods designed for 3-D applications are evaluated. An efficient solution procedure is obtained.
- Work currently underway
  - Unsteady SSME-rig1 simulations by using 34.3 Million grid points.
  - Experimental measurements at NASA-MSFC.